Original Paper

The Higgs boson, Supersymmetry and Dark Matter

Relations and Perspectives

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The discovery of a light Higgs boson at the LHC opens a broad program of studies and measurements to understand the role of this particle in connection with New Physics and Cosmology. Supersymmetry is the best motivated and most thoroughly formulated and investigated model of New Physics which predicts a light Higgs boson and can explain dark matter. This paper discusses how the study of the Higgs boson connects with the search for supersymmetry and for dark matter at the LHC and at a future e^+e^- collider and with dedicated underground dark matter experiments.

1 Introduction

The discovery of a light Higgs boson [1, 2] has opened a new chapter in the search for new physics and its connection to cosmology through dark matter (DM). The properties of the Higgs boson may be sensitive to new physics beyond the Standard Model (BSM), either because the particle observed by ATLAS and CMS is part of an extended Higgs sector or because new particles may modify its couplings and decay rates compared to those predicted by the Standard Model (SM). If dark matter is due to a weakly-interacting massive particle (WIMP), the Higgs boson most likely couples to it. In this case it may have a major role in mediating the WIMP interactions, which have set its relic density in the universe to the observed level, and those which are being exploited to detect dark matter interactions in underground experiments. In all these cases, the study of the Higgs boson properties, the search for BSM physics at colliders and the direct searches for dark matter at dedicated experiments will likely shape a new picture of particle physics and cosmology, which integrates the Higgs boson as a central piece.

Supersymmetry (SUSY) has been so far the best motivated and most thoroughly formulated and investigated model of BSM physics, which predicts the Higgs boson to be light and naturally incorporates dark matter. Originally introduced to solve the hierarchy problem of the SM, SUSY with conserved R-parity offers a remarkable signature of its production in collider experiments: SM particles + missing energy. Its lightest particle, which is stable, takes the role of the WIMP, explaining the observed DM relic density for a broad range of SUSY model parameters. Even if SUSY is not realised in nature, its study is of great interest since it represents an attractive template of BSM theories with a conserved quantum number.

In this paper, we discuss the current status and future perspectives for the study of the Higgs boson in relation to BSM physics, here taken to be supersymmetric, and dark matter. The results of the Higgs property measurements and of the searches for BSM physics conducted on the data collected by the LHC experiments at 7 and 8 TeV and the bounds set on the WIMP scattering cross section by the Xenon [3] and LUX [4] experiments already provide a formidable set of measurements and constraints. The forthcoming LHC run at 13-14 TeV will extend the number of processes tested and the accuracy of their measurements in the study of the Higgs boson profile [5]. The sensitivity to new particles will be greatly boosted by the increase in both energy and integrated luminosity, significantly extending it well beyond 1 TeV for the majority of the SUSY states. The anticipated sensitivity of the LZ data will push the WIMP scattering cross section bounds down by more than two orders of magnitude [6, 7].

The past two decades have been rich in technical and conceptual developments, which now make it possible to envisage new colliders of unprecedented luminosity and energy [8, 9]. An e^+e^- collider of luminosity in excess

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to 10^{34} cm^{-2} s^{-1} and energy up to ~1 TeV based on superconducting cavities is technically feasible and the ILC project is now being considered for construction [10]. The luminosity of the LHC can be increased by a factor of~10 to deliver an astonishing 3 ab^{-1} of integrated luminosity with the HL-LHC program by ~2035. A circular hadron collider with collision energy in the range 80-100 TeV can be realistically envisaged for the 2040s (FCC-hh), housed in a tunnel which could also be used for an e^+e^- collider of energy up to the HZ threshold (FCC-ee) [11]. On the time scale of the HL-LHC and a possible ILC, DM direct detection experiments of third generation could explore the region of scattering cross section values down to the limit where neutrino scattering becomes an irreducible background [7].

Here, we do not attempt to be exaustive in discussing the complex inter-relations between the Higgs sector, SUSY and DM. Rather, we wish to highlight some aspects, emerged from our studies of parameteric scans of the SUSY phase space which can be investigated in some details with the data already at hand and offer promising perspectives for the forthcoming LHC runs as well as for future colliders. First, we want to highlight that the SUSY squark and gluino contributions to the light Higgs decay branching fractions may remain sizeable for SUSY particle masses well beyond the sensitivity of the LHC direct searches. For appropriate combinations of the SUSY parameters, the precision study of the Higgs decay properties at the LHC and an e^+e^- collider may thus reveal SUSY signals, even if the SUSY mass scale is beyond the LHC kinematic reach. Then, we consider the interplay between the Higgs sector and dark matter, if this is of supersymmetric nature. The contribution of the Higgs to the neutralino scattering cross section and the complementarity of the region of parameter space, where the Higgs couplings and the WIMP neutralino scattering can give signals from BSM physics, offer new opportunities to test SUSY using data from collider and dark matter direct detection experiments.

2 The phenomenological MSSM, dark matter and colliders

The minimal supersymmetric extension of the SM (MSSM) is the most economical implementation of supersymmetry, which introduces only two Higgs doublets resulting in five physical Higgs particles. Additional Higgs singlets or doublets can also be considered, for example in the so-called NMSSM, and result in an increase of the complexity of the relations between the Higgs, supersymmetric and SM sectors with the increased number of parameters of the model. However, these extensions are not required, nor suggested, by the present data and here we consider the minimal SUSY implementation in the MSSM.

The study of the relations between the Higgs sector, new physics and dark matter in the MSSM can be aptly performed in the so-called phenomenological MSSM (pMSSM). This 19-parameter implementation of the MSSM offers the freedom and generality of a model where all the SUSY particle masses are free and independent, while keeping the number of parameters manageable for extensive scans [12]. The pMSSM is becoming a widely recognised framework to evaluate the impact of the LHC bounds on the MSSM viability and is being used in both phenomenological studies [13–19] and by the LHC experiments [20, 21]. In this study, we take the lightest neutralino to be the LSP and the values of all SUSY particle masses are varied, independently, up to 5 TeV, the SUSY trilinear couplings in the range -15 to 15 TeV and $2 < \tan\beta < 60$ in flat scans. These ranges are important because the values of the fractions of pMSSM points allowed or excluded by the various constraints discussed later in the paper depend on them. Details on the programs used for performing the pMSSM scans, computing the SUSY spectra and the related observables and the constraints imposed on the accepted pMSSM points from low energy data and flavour physics can be found in [15]. Only points with the lightest Higgs mass in the range $123 < M_h < 128$ GeV, compatible with the ATLAS and CMS measurements when accounting for systematic and model uncertainties, are accepted.

The pMSSM gives a clear view onto the scenarios of neutralino dark matter without the biases introduced by the highly constrained versions of the MSSM, such as the CMSSM, which were widely used for benchmark studies and the studies of supersymmetric dark matter before the start of the LHC. The WIMP "miracle" paradigm has that a particle of mass ~100 GeV with typical weak-interaction couplings generates exactly the correct amount of dark matter relic density observed in the universe. In reality, within a well-defined model the couplings are controlled by several model parameters and interactions with other new particles may alter the WIMP density, resulting in significant modifications of the range of the viable WIMP masses. The annihilation cross section varies with the nature of the neutralino LSP and co-annihilation may reduce the neutralino density, we observe that χ_1^0 masses as low as 10 GeV (for bino-like neutralinos) and as large as 3.5 TeV (for wino-like neutralinos) can be comfortably accomodated by the cosmic microwave background (CMB) data, as illustrated in Figure 1 obtained from the results of our pMSSM scans. We test two sets of $\Omega_\chi h^2$ constraints

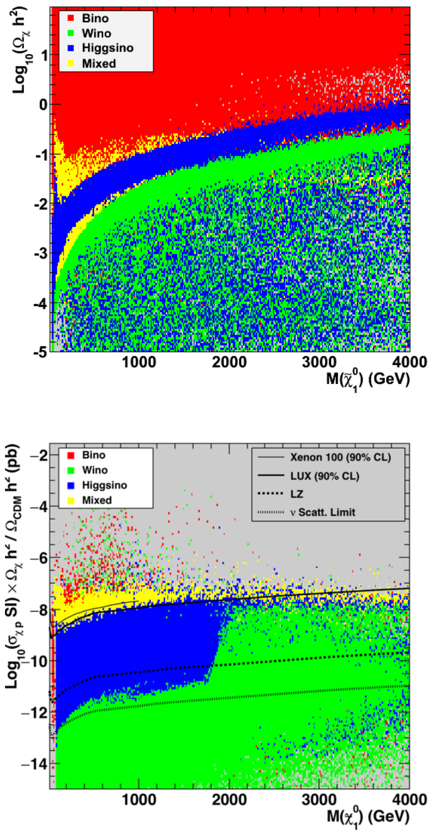

Figure 1 (online color at: www.ann-phys.org) Neutralino relic density (upper panel) and scaled scattering cross section (lower panel) in the MSSM as a function of its mass. The colours indicate the nature of the neutralino LSP.

for the pMSSM points with neutralino LSP. First, we apply a strict bound requiring the neutralino relic density is in agreement with the dark matter relic density obtained from the PLANCK data, $\Omega_{CDM} h^2$ [22], allowing for systematic uncertainties, i.e. $0.090 < \Omega_\chi h^2 < 0.163$. Then, we also consider a looser constraint, by requesting that the neutralino relic density does not exceed the upper bound on the dark matter density from the CMB data, i.e. $10^{-5} < \Omega_\chi h^2 < 0.163$, again after acconting for systematic uncertainties. This allows for additional sources of dark matter, other than the neutralino LSP. In this case, it is appropriate to rescale the χ scattering cross section for the neutralino LSP case by the ratio of the neutralino relic density to the CMB value, referred to in the following as "scaled scattering cross section".

For this study we consider the constraints derived from the LHC data obtained in the 7+8 TeV runs, the results from direct DM searches at LUX [4] and the perspectives for the LHC Run 2, the HL-LHC program, the ILC and LZ. The expected accuracies for the determination of the Higgs properties for the future programs are taken from the compilation in [5]. The ATLAS and CMS experiments at the LHC have pursued a vast program of searches for SUSY particles. We test the compatibility of the accepted pMSSM points with the bounds implied by a selection of these searches. Event samples are generated and a parametric simulation for the event reconstruction is performed. We apply the signal selection criteria for the ATLAS analyses in the jets+MET [23], b-jets+MET [24], ℓ(s)+(b)jets+MET [25,26], 2 & 3 ℓs+MET [27,28], ℓ+bb+MET [29] channel, the ATLAS and CMS searches in the mono-jet channel [30, 31] and the CMS search for $H/A \to \tau\tau$ [32]. The number of SM background events in the signal regions are taken from the estimates by the experiments and rescaled accordingly for the future projections. The 95% confidence level (C.L.) exclusion of each SUSY point in presence of background only is determined using the CLs method [33].

3 Higgs sensitivity to SUSY

The lightest MSSM Higgs boson, h^0, represents the supersymmetric counterpart of the SM Higgs boson, H^0_{SM}. It is well known that the effects of the extended Higgs sector and loops of SUSY particles, mostly $\tilde{t}$, $\tilde{b}$, $\tilde{\tau}$ and $\chi^\pm$ may result in shifts of the h^0 couplings to fermions and gauge bosons compared to those of the SM Higgs boson and thus affect its decay widths and branching fractions [18, 34]. These effects, if detected in the precision study of the Higgs profile at the LHC and an e^+e^- collider, may not only indirectly signal the existence of supersymmetry but also point to the value of some of the SUSY parameters.

In our study we test the compatibility of the Higgs properties for each accepted pMSSM point with those predicted for the SM Higgs by computing the χ^2 probability for the Higgs signal strengths normalised to its SM expectation, $\mu = (\sigma \times \mathrm{BR})/(\sigma \times \mathrm{BR})|_{SM}$, of the $h \to bb$, $\tau\tau$, WW, ZZ and $\gamma\gamma$ channels for the LHC and for the branching fractions of the $h \to bb$, cc, $\tau\tau$, WW, ZZ and $\gamma\gamma$ channels for an e^+e^- collider.

An interesting question arises concerning the indirect sensitivity to new physics through the study of the Higgs branching fractions compared to the direct sensitivity from LHC searches in the MET and other channels. The rapid increase of the mass bounds for SUSY particles at the LHC and the expected $1/M^2$ decrease of the effect of new particles to the Higgs couplings brings into question the role of the precision study of the Higgs profile by the time when hundreds of fb^{-1} of 14 TeV will have been collected by ATLAS and CMS. The answer to this question depends largely on the particle under consideration.

The extended Higgs sector of the MSSM modifies the lightest Higgs couplings to up- and down-type quarks by terms which scale inversely with the CP-odd A boson mass as $2M_Z^2/M_A^2 \tan^2\beta$ and $2M_Z^2/M_A^2$, respectively [34]. These give an indirect sensitivity to the scale of M_A, if deviations in the branching fractions to up- and down-type quarks are detected, or a lower bound on M_A, if the coupling properties agree with the SM predictions. The size of the effect on the coupling decreases as $1/M_A^2$. The direct sensitivity to the A^0 (and H^0) boson at the LHC comes, at present, mostly from the $pp \to A \to \tau^+\tau^-$ process. The bbH associate production and gluon fusion processes [35] result in a decrease of the total cross section $\propto \tan\beta$ up to the point where the b loops take over and the cross section increases. The decay branching fraction is $\propto \tan\beta$ for $\tan\beta < 10$. All this makes the bounds from the $\tau\tau$ final state particularly strong at large values of $\tan\beta$ but quite unconstraining at $\tan\beta \simeq 10$.

Looking to the modifications of the Higgs couplings to fermions induced by loops of strongly-interacting SUSY particles, the case of the Δ_b-induced shift of the Higgs coupling to bb, and thus all the Higgs branching fractions, is of special importance. The SUSY contribution scales as $\mu \tan\beta M_{\tilde{g}}/M^2_{\tilde{g},\tilde{b},\tilde{t}}$ and the SUSY strongly-interacting sector does not decouple, since the value of the $\mu\tan\beta$ term can be taken to be much larger than the mass of the SUSY particles appearing at the denominator. Under these circumstances the study of the Higgs branching fractions, or the Higgs signal strengths, can unveil SUSY scenarios with strongly-interacting particle at masses well beyond the kinematic reach of the LHC.

Results for the sensitivity to SUSY mass scales are summarised in Figure 2, which compares the direct and indirect sensitivity to M_A and to the mass of the gluino and scalar quarks of third generation as a function of the energy and integrated luminosity of the LHC samples.

In the case of M_A, the most stringent constraint is obtained from the analysis of the Higgs signal strengths and requires $M_A > 350$ GeV for any value of $\tan\beta$ [36, 37]. This is due to the weakness of the mass bound obtained in the $\tau\tau$ channel at low values of $\tan\beta$, where the product of production cross section and decay branching fraction for $pp \to H \to \tau\tau$ becomes too small to be constrained by the current LHC data. With the increased energy and luminosity of the Run 2 and then the HL-LHC program, the direct LHC searches for $A \to \tau\tau$ but also the WW, ZZ and tt channels, important at small $\tan\beta$ values, are expected to extend the sensitivity well beyond the value of 600-700 GeV, where M_A effectively decouples and the indirect sensitivity from the Higgs couplings saturates, independent of the value of $\tan\beta$. The constraint on M_A is particularly important in relation to dark matter for predicting the neutralino relic density, since neutralino annihiliation through the A pole, $\chi\chi \to A \to b\bar{b}$, is a major mechanism for setting the neutralino density in the early universe, when $M_\chi \simeq M_A/2$.

On the contrary, for $\mu\tan\beta$ values of $\mathcal{O}(100$ TeV$)$, SUSY points with squark and gluino masses larger than 4 TeV would have the Higgs decay properties deviating enough from the SM to be identifiable with the accuracy anticipated for the HL-LHC and the ILC, i.e. a factor of ~2 larger compared to the anticipated direct sensitivity from MET searches at the LHC. However, it must be always kept in mind that the indirect sensitivity depends on the specific values of some parameters, namely μ and $\tan\beta$, while the direct bounds are generally much less affected by parametric dependencies. This underlines the

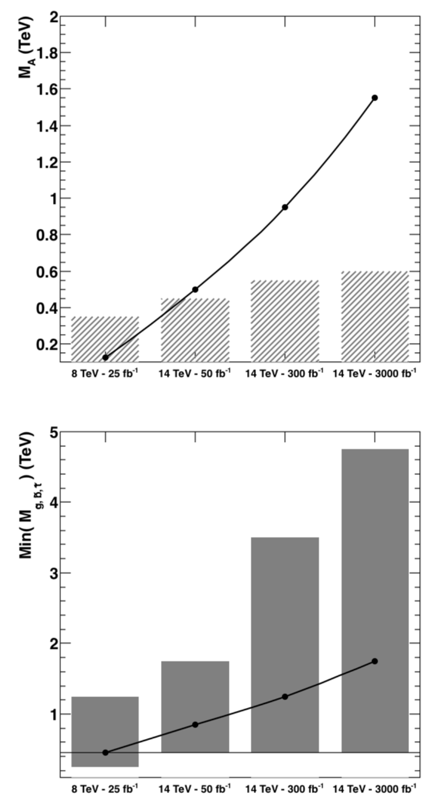

Figure 2 Sensitivity to the mass of the CP-odd A boson (upper panel) and the lightest state among $\tilde{g}$, $\tilde{b}$ and $\tilde{t}$ (lower panel) as a function of the energy and luminosity stages of the LHC program for pMSSM points. The 95% C.L. exclusion bounds are given for the direct search by the continuous line and for the indirect contraints from the h decay properties by the filled bars. These show the exclusion range when the MSSM paramaters are varied as described in the text. The region shaded in grey has no pMSSM solutions fulfilling the low-energy and flavour physics constraints.

importance of the complementarity of indirect sensitivity through measurements of the Higgs properties and direct searches [38].

4 DM and the Higgs sector

The complementarity between direct searches for SUSY at the LHC, dark matter at direct and indirect detection experiments has already been highlighted in the framework of the pMSSM in [19]. What has not been discussed in much detail are the relations between the Higgs sector and dark matter. If dark matter is due to the lightest SUSY particle (LSP) behaving as a WIMP, Higgs bosons should in principle couple to it. This has three important consequences. First, the Higgs can decay into dark matter particle pairs, thus generating a possibly sizeable invisible Higgs decay width. Then, the Higgs exchange diagram contributes to the scattering cross section of WIMPs on nucleons and DM particles may annihilate through a Higgs resonance. Last, there is an important correlation between the WIMP scattering cross section and the Higgs phenomenology at the LHC and ILC. The parameter space where large SUSY corrections to the Higgs may be revealed by precision measurements of its decay branching fractions appears to be complementary to that explorable by the next generation of DM direct detection experiments. Here we discuss these scenarios in details.

4.1 Invisible Higgs Decays

If the lightest LSP neutralino has a mass $M_\chi < M_h/2$, then the $h \to \chi\chi$ decay channel is kinematically open and the Higgs boson may acquire a non-zero invisible width.

However, since the $h\chi\chi$ coupling also controls the χp scattering cross section and may contribute to the neutralino annihilation cross section there is a correlation between the rate of $h \to \chi\chi$, the scattering cross section and the neutralino relic density, where the current bounds place some non-trivial constraints. Figure 3 shows this correlation. SUSY points with neutralino relic density compatible with that extracted from the analysis of CMB data may have a large Higgs branching fraction into neutralino pair, even larger than the limit already obtained by the analysis of the Higgs properties at the LHC. But it is important to observe that a large invisible Higgs branching fraction implies a large neutralino scattering cross section, because they are both due to an enhanced $h\chi\chi$ coupling. The LUX upper limit on the cross section for values of the neutralino mass below $M_h/2$ removes almost entirely

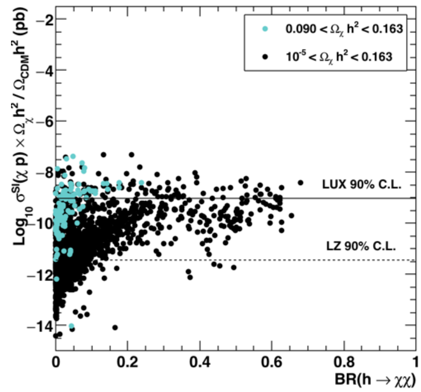

Figure 3 (online color at: www.ann-phys.org) Neutralino scattering cross section as a function of its mass for points with $\Omega_\chi h^2$ compatible with the CMB data (cyan dots) and scaled value for those with $\Omega_\chi h^2 < \Omega_{CDM} h^2$ (black dots). The horizontal lines indicate the current LUX (continuous) and expected LZ (dashed) 90% C.L. upper limits for WIMP masses between 46 and 62 GeV.

the MSSM solutions having BR($h \to \chi\chi$) above 0.15, if the neutralino is the only source of dark matter. The LZ experiment will lower this bound to ~ 0.10 even in the case $\Omega_\chi h^2$ does not saturate the relic density measured on CMB data Therefore, if the neutralino LSP alone is responsible for dark matter and the assumptions on the dark matter density in our galaxy are correct, it is unlikely that the invisible Higgs rate is very significant, it may even be too small to be directly observable at the LHC. There has been a significant effort in optimising the LHC sensitivity to invisible Higgs decays, from fits to rates the observed modes [39, 40] to studies of the associated VH production [41, 42]. However, achieving sensitivity to invisible rates below 10% appears very challenging [43]. An e^+e^- collider will have, on the contrary, the possibility to detect and measure an invisible partial width of just a few percent [44], which makes it unique for exploring this intriguing scenario.

4.2 Higgs and DM direct detection

If the neutralino WIMP is heavier than half the Higgs mass, the invisible $h \to \chi\chi$ decay is forbidden. Still, the Higgs coupling to the neutralino is relevant to dark matter phenomenology. The WIMP scattering cross section receives contributions from the Higgs exchange and is inversely proportional to the Higgsino mass parameter, μ, as illustrated in Figure 4. Therefore, there are two complementary regions in the SUSY parameter space: the first, where $\mu \tan\beta$ is large, the neutralino scattering cross sec-

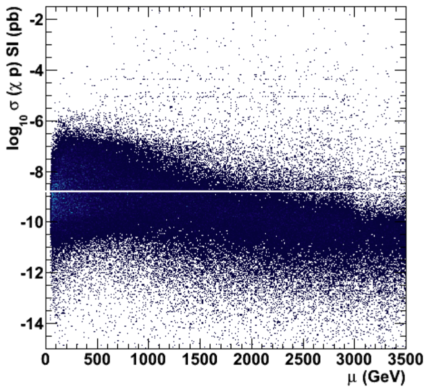

Figure 4 (online color at: www.ann-phys.org) Neutralino scattering cross section as a function of the Higgsino mass parameter μ for pMSSM points. The horizontal line represents the current LUX bound.

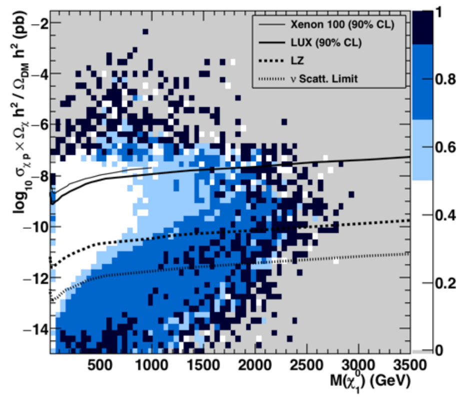

Figure 5 (online color at: www.ann-phys.org) Fraction of pMSSM point not excluded by the LHC 7+8 TeV data and excluded at 95% C.L. by the analysis of the Higgs branching fractions with the accuracy expected at a 1 TeV ILC in the plane defined by the neutralino mass and the scaled neutralino scattering cross section compared to the scattering cross section current and future upper limits. The colours show the regions where more than 50% (light blue), 68% (blue) and 90% (dark blue) of the points are excluded.

tion is small, the strongly-interacting SUSY particles do not decouple and the Higgs branching fractions remain significantly different from their SM predictions, and the second, where the neutralino scattering cross section is large enough to be tested by dark matter direct detection experiments while the heavy SUSY degrees of freedom decouple in the Higgs sector and the Higgs properties are SM-like. This has the important consequence that, in case neither the LHC and, possibly, the ILC studies of the Higgs profile would reveal a deviation from the SM, nor the LZ data would detect a WIMP signal, a very significant fraction of the parameter space of the MSSM with neutralino LSP could be excluded (see Figure 5).

This is demostrated in quantitative terms in Table 1, which summarises the fraction of our pMSSM points with SUSY masses up to 5 TeV excluded by the LHC MET searches only and by the addition of the Higgs data (at LHC and ILC) and the DM direct searches for the loose Ωh^2 constraints. Requiring the neutralino to saturate the relic density decreases the fraction of points excluded by the LHC at 14 TeV by about 12% due to the shift of wino χ_1^0 points towards larger masses, but does not significantly affect the overall results when the Higgs and direct dark matter constraints are applied. Independent of the LHC energy and statistics considered, the inclusion of the Higgs data always significantly increases the fraction of SUSY scenarios which can be tested and excluded, if the Higgs properties turn out to be SM-like. The combined analysis of the LHC, ILC and LZ data, assuming no signal is observed, should provide bounds stringent enough to exclude almost 97% of the pMSSM points we have generated and having SUSY masses up to 5 TeV. If a signal is observed, crucial tests can be carried to ensure that the nature of the WIMP dark matter is identified.

Table 1 Fractions of pMSSM points excluded by the combination of LHC MET searches, LHC and ILC Higgs data and LZ DM direct detection

	LHC 8	**LHC**	**LHC**	**HL-LHC**
	8 TeV	14 TeV	14 TeV	14 TeV
	25 fb^{-1}	50 fb^{-1}	300 fb^{-1}	3 ab^{-1}
js+ℓs+MET	0.145	0.570	0.698	0.820
+h^0 μs	0.317	0.622	0.793	0.920
+ILC h^0 BRs	0.588	0.830	0.890	0.945
+LZ		0.914	0.940	0.964

The complementarity between the indirect probe through the Higgs measurements and the direct SUSY searches in the MET channels at colliders is thus integrated by the DM direct detection data. The anticipated precision of an e^+e^- collider is crucial in this context. Together, all these data could test in details supersymmetry as the theory of new physics in relation to dark matter.

5 Conclusions

The discovery of a light Higgs boson at the LHC constitutes a major step towards the experimental test of models of new physics and the investigation of their relation to dark matter. If this is due to a WIMP, then the Higgs boson most likely couples to it and to the other particles of the

underlying SM extension. Supersymmetry represents a well motivated implementation of new physics incorporating a light Higgs boson and a dark matter candidate.

Dark matter introduces a number of important constraints on the SUSY parameter space when the neutralino is the WIMP and bound by dark matter data. The contribution of the Higgs to the neutralino scattering cross section offers opportunities to test SUSY which are complementary to those available at colliders.

SUSY contributions which shift the coupling of the Higgs to b quarks and therefore modify all its decay branching fractions do not decouple for large values of the mass of the strongly interacting particles if the product of $\mu \tan\beta$ is large. Therefore, Higgs precision measurements retain their sensitivity to SUSY corrections, even if the direct searches in the MET channels with the 14 TeV LHC data do not obtain signals of SUSY states.

The complementarity between the indirect probe through precision Higgs measurements, the direct SUSY searches in the MET channels at colliders is also integrated by the DM direct detection data. This complementarity is highlighted by the observation that the region of parameter space where the Higgs couplings and the WIMP neutralino scattering can give signals beyond the SM are largely complementary. The anticipated precision of an e^+e^- collider is crucial to maximise this complementarity. There are excellent perspectives that the combination of these data will test in details supersymmetry as the theory of new physics, if this is indeed reponsible for dark matter.

Key words. Higgs, SUSY, dark matter.

References

[1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716** (2012) 1 [arXiv:1207.7214 [hep-ex]].
[2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716** (2012) 30 [arXiv:1207.7235 [hep-ex]].
[3] E. Aprile *et al.* [XENON100 Collaboration], Phys. Rev. Lett. **109** (2012) 181301 [arXiv:1207.5988 [astro-ph.CO]].
[4] D. S. Akerib *et al.* [LUX Collaboration], Phys. Rev. Lett. **112** (2014) 9, 091303 [arXiv:1310.8214 [astro-ph.CO]].
[5] S. Dawson *et al.*, arXiv:1310.8361 [hep-ex].
[6] D. C. Malling *et al.*, arXiv:1110.0103 [astro-ph.IM].
[7] P. Cushman *et al.*, arXiv:1310.8327 [hep-ex].
[8] W. Barletta, M. Battaglia, M. Klute, M. Mangano, S. Prestemon, L. Rossi and P. Skands, Nucl. Instrum. Meth. A **764** (2014) 352.
[9] W. A. Barletta *et al.*, arXiv:1401.6114 [hep-ex].
[10] T. Behnke *et al.*, arXiv:1306.6327 [physics.acc-ph].
[11] F. Zimmermann, M. Benedikt, D. Schulte and J. Wenninger, IPAC-2014-MOXAA01.
[12] A. Djouadi *et al.*, hep-ph/9901246.
[13] S. S. AbdusSalam *et al.* Phys. Rev. D **81** (2010) 095012 [arXiv:0904.2548 [hep-ph]].
[14] S. Sekmen *et al.*, JHEP **1202** (2012) 075 [arXiv:1109.5119 [hep-ph]].
[15] A. Arbey, M. Battaglia and F. Mahmoudi, Eur. Phys. J. C **72** (2012) 1847 [arXiv:1110.3726 [hep-ph]].
[16] A. Arbey, M. Battaglia, A. Djouadi and F. Mahmoudi, JHEP **1209** (2012) 107 [arXiv:1207.1348 [hep-ph]].
[17] M. W. Cahill-Rowley, J. L. Hewett, A. Ismail and T. G. Rizzo, Phys. Rev. D **88** (2013) 3, 035002 [arXiv:1211.1981 [hep-ph]].
[18] A. Arbey, M. Battaglia, A. Djouadi and F. Mahmoudi, Phys. Lett. B **720** (2013) 153 [arXiv:1211.4004 [hep-ph]].
[19] M. Cahill-Rowley *et al.*, Phys. Rev. D **91** (2015) 5, 055011 [arXiv:1405.6716 [hep-ph]].
[20] CMS Collaboration, CMS-PAS-SUS-12-030.
[21] CMS Collaboration, CMS-PAS-SUS-13-020.
[22] P. A. R. Ade *et al.* [Planck Collaboration], Astron. Astrophys. (2014) [arXiv:1303.5076 [astro-ph.CO]].
[23] [ATLAS Collaboration], Note ATLAS-CONF-2013-047.
[24] [ATLAS Collaboration], Note ATLAS-CONF-2013-053.
[25] G. Aad *et al.* [ATLAS Collaboration], JHEP **1406** (2014) 124 [arXiv:1403.4853 [hep-ex]].
[26] [ATLAS Collaboration], Note ATLAS-CONF-2013-037.
[27] [ATLAS Collaboration], Note ATLAS-CONF-2013-049.
[28] [ATLAS Collaboration], Note ATLAS-CONF-2013-035.
[29] [ATLAS Collaboration], Note ATLAS-CONF-2013-093.
[30] [CMS Collaboration], Note CMS PAS EXO-12-048.
[31] [ATLAS Collaboration], Note ATLAS-CONF-2013-068.
[32] [CMS Collaboration], Note CMS PAS HIG-13-021.
[33] A. L. Read, J. Phys. G **28** (2002) 2693.
[34] A. Djouadi, Phys. Rept. **459** (2008) 1 [hep-ph/0503173].
[35] M. Muhlleitner, H. Rzehak and M. Spira, DESY-PROC-2010-01.
[36] L. Maiani, A. D. Polosa and V. Riquer, Phys. Lett. B **724** (2013) 274 [arXiv:1305.2172 [hep-ph]].
[37] A. Arbey, M. Battaglia and F. Mahmoudi, Phys. Rev. D **88** (2013) 1, 015007 [arXiv:1303.7450 [hep-ph]].
[38] M. Cahill-Rowley, J. Hewett, A. Ismail and T. Rizzo, Phys. Rev. D **90** (2014) 9, 095017 [arXiv:1407.7021 [hep-ph]].
[39] J. R. Espinosa, M. Muhlleitner, C. Grojean and M. Trott, JHEP **1209** (2012) 126 [arXiv:1205.6790 [hep-ph]].
[40] G. Belanger *et al.*, Phys. Lett. B **723** (2013) 340 [arXiv:1302.5694 [hep-ph]].
[41] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. Lett. **112** (2014) 201802 [arXiv:1402.3244 [hep-ex]].
[42] S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **74** (2014) 8, 2980 [arXiv:1404.1344 [hep-ex]].
[43] H. Okawa, J. Kunkle and E. Lipeles, arXiv:1309.7925 [hep-ex].
[44] M. Schumacher, LC-PHSM-2003-096.